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new leverage on challenging weed problems?

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Transdisciplinary weed research: new leverage on challenging weed problems?

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Summary

Transdisciplinary weed research (TWR) is a promising path to more effective management of challenging weed problems. We define TWR as an integrated process of inquiry and action that addresses complex weed problems in the context of broader efforts to improve economic, environmental and social aspects of ecosystem sustainability. TWR seeks to integrate scholarly and practical knowledge across many stakeholder groups (e.g. scientists, private sector, farmers and extension officers) and levels (e.g. local, regional and landscape). Furthermore, TWR features democratic and iterative processes of decision-making and collective action that aims to align the interests, viewpoints and agendas of a wide range of stakeholders. The fundamental rationale for TWR is that many challenging weed problems (e.g. herbicide resistance or extensive plant invasions in natural areas) are better addressed systemically, as a part of broad-based efforts to advance ecosystem sustainability, rather than as isolated problems. Addressing challenging weed problems systemically can offer important new leverage on such problems, by creating new opportunities to manage their root causes and by improving complementarity between weed management and other activities. While promising, this approach is complicated by the multidimensional, multilevel, diversely defined and unpredictable nature of ecosystem sustainability. In practice, TWR can be undertaken as a cyclic process of (i) initial problem formulation, (ii) 'broadening' of the problem formulation and recruitment of stakeholder participants, (iii) deliberation, negotiation and design of an action agenda for systemic change, (iv) implementation action, (v) monitoring and assessment of outcomes and (vi) reformulation of the problem

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situation and renegotiation of further actions. Notably, 'purposive' disciplines (design, humanities and arts) have central, critical and recurrent roles in this process, as do integrative analyses of relevant multidimensional and multilevel factors, via multiple natural and social science disciplines. We exemplify this process in prospect and retrospect. Importantly TWR is not a replacement for current weed research; rather, the intent is to powerfully leverage current efforts.

Keywords: agroecosystem processes, systems research, ecosystem services, crop protection, interdisciplinary research, multistakeholder processes.

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Introduction

Weeds have strong effects on a wide range of biophysical, economic and social dimensions of managed ecosystems. For this reason, improvements in weed management are essential to the sustainable development of these ecosystems (Radosevich *et al.*, 2007). Sustainable development implies improving the performance of managed ecosystems in economic, biophysical and social terms. To support such holistic improvement, weed management must meet a high standard; it must become more effective in limiting losses of food and other material yields, more supportive of other ecosystem services (Jordan & Vatovec, 2004; Bommarco *et al.*, 2013) and more socially just (Loos *et al.*, 2014).

At present, weed research is largely organised and conducted in a mono-disciplinary fashion, with emphasis on biophysical aspects of weed problems such as yield loss (Fig. 1; Ward *et al.*, 2014). It is important to recognise that such disciplinary research is essential to understanding and managing weed problems, particularly in situations where questions are clear cut and timely information is needed. Moreover, there are notable examples of weed research programmes that address social factors and take widely interdisciplinary approaches (e.g. Graham, 2013; Ervin & Jussaume, 2014; Matzek *et al.*, 2014; Zwickle *et al.*, 2014; Seastedt, 2015; Ervin & Frisvold, 2016).

Numerous observers have called for more weed research that is informed by its broader environmental and social context, so that it can successfully address highly challenging weed problems. Such problems include (but are not restricted to) herbicide resistance (Jussaume & Ervin, 2016), invasive crops or perennial weeds in tropical smallholder agriculture (e.g. Davis *et al.*, 2009; Allen *et al.*, 2014; Schut *et al.*, 2014a; Ward *et al.*, 2014; Jordan & Davis, 2015). All of these

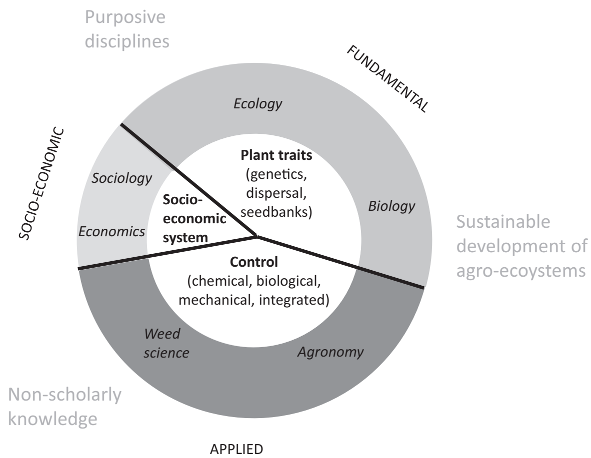

Fig. 1 The current scope of weed research, which presently focuses on traits of weedy plants and on their management, while social aspects receive less emphasis. Elements highly relevant to transdisciplinary weed research but presently of marginal importance are illustrated in grey.

observers call for weed research to continue to expand by engagement with a wide range of scholarly disciplines and societal stakeholders.

Despite repeated calls for expansion of weed research by wide engagement with scholarly disciplines and societal stakeholders, there is need for a practical model that provides specific recommendations for the initiation and conduct of expanded and engaged weed research. In this article, we outline such a model and its conceptual basis, drawing on a range of conceptual developments and practical experience. The genesis of this article was an international workshop (June 2014) that convened 35 weed researchers from a range of different disciplines and global regions. Attendees worked to articulate a model for expansion of weed research, building on outcomes from a similar workshop held in 2012 (Ward *et al.*, 2014). Importantly the model outlined below is intended to leverage and complement, not to replace, ongoing disciplinary weed research. Before presenting the model, we state several important premises.

Premise 1: Challenging weed problems can be addressed via broad-based efforts to advance ecosystem sustainability

Ecosystem sustainability projects (e.g. Olsson *et al.*, 2007; Mapfumo *et al.*, 2015) seek holistic improvement in the performance of managed ecosystems, that is by making improvements in economic, biophysical and social aspects of these ecosystems. Addressing challenging weed problems in the context of such projects creates new opportunities to deal with the root causes of such problems and improves complementarity between weed management and other activities. How can these new opportunities arise? In general, addressing root causes and improving complementarity of weed management requires systemic changes in biophysical, technological, sociocultural, economic, institutional and political factors affecting a managed ecosystem (Liebman *et al.*, 2016). Many barriers stand in the way of such changes. To surmount these barriers and achieve systemic change that improves weed management, we posit that collective action is generally required.

Collective action on ecosystem sustainability can achieve systemic change by drawing on the resources and power of multiple groups and organisations concerned with the sustainability of a managed ecosystem (Sayer *et al.*, 2013; Opdam *et al.*, 2015). To mobilise such collective action, 'win-win' or 'both/and' management strategies are generally needed (Sayer *et al.*, 2013). These are strategies that address both weed problems and other ecosystem sustainability problems. Our premise is that identification of such strategies, and mobilisation of collective action to implement them, is a promising pathway to achieving systemic change needed for durable improvement in management of challenging weed problems. Obviously, to explore this pathway, weed researchers must address such weed problems as part of broader projects on ecosystem sustainability.

To illustrate this point, we offer the example of herbicide resistance management. Arguably, herbicide resistance is often unmanageable in low-diversity agroecosystems in which herbicides are the primary means for weed control (Mortensen *et al.*, 2012). In these situations, diversification of weed management methods is needed to avoid herbicide resistance. Broad diversification of methods often requires broader agroecosystem diversification (Liebman *et al.*, 2016), in which diversity of crops enables diversification of weed management (e.g. Davis *et al.*, 2012). Therefore, weed researchers concerned with herbicide resistance might gain new leverage by participating in efforts to promote agroecosystem diversification. Of course, agroecosystem diversification (Kremen & Miles, 2012) is not only undertaken to improve weed management. Generally, diversification projects (e.g. Steingröver *et al.*, 2010) are undertaken to improve multiple aspects of the performance of managed ecosystems in biophysical, economic and social terms. Moreover, such projects typically strive to engage stakeholders in sectors beyond science and agricultural production, as the agendas, resources and engagement of these stakeholders are vital to successful ecosystem management (Opdam *et al.*, 2015).

By participating in projects to advance agroecosystem diversification, weed researchers can expand both the scope and societal engagement of their work, as recommended by many observers (Davis *et al.*, 2009; Allen *et al.*, 2014; Schut *et al.*, 2014a; Ward *et al.*, 2014). By collaborating in diversification projects that span multiple objectives and societal sectors, weed researchers can gain new leverage on herbicide resistance, using approaches to manage or prevent resistance that are possible only in diversified agroecosystems (Davis *et al.*, 2012). New leverage is also gained by improving the complementarity of weed management with other management efforts associated with diversification. We conclude that the strategy outlined above, that is undertaking research on complex weed problems as part of projects that address multiple aspects of ecosystem sustainability and multiple social and biophysical factors, has high potential to improve the impact of weed research on difficult weed problems.

Premise 2: Ecosystem sustainability challenges are complex problems

Most ecosystem sustainability challenges have characteristic features of so-called complex problems**.** Following a stream of scholarship that has elucidated the nature and significance of such problems (Rittel & Webber, 1973; Funtowicz & Ravetz, 1994; Schut *et al.*, 2014a), we define complex problems as the following: (i) multidimensional, (ii) characterised by feedback and multiscale dynamics that create uncertainty and unpredictability and (iii) involving multiple stakeholder groups that do not have a common understanding of the problem and potential solutions.

First, complex ecosystem sustainability challenges are affected by a wide range of biophysical, technological, sociocultural, economic, institutional and political factors, and thus have many causes. As well, many different aspects of managed ecosystems are of potential concern to stakeholders interested in economic, environmental and social aspects of sustainability. Because of this multiplicity of both causal factors and outcome variables (i.e. aspects of concern), ecosystem sustainability challenges are highly multidimensional and even 'simple' weed management practices (e.g. herbicide-based management) reflect the operation of many different factors and constraints.

Second, complex ecosystem sustainability challenges are characterised by high unpredictability, due to incomplete understanding of relevant factors and their interactions. Moreover, even if understanding was relatively complete, unpredictability arises also from complicated dynamics rooted in feedbacks among biophysical, social–cultural and other factors (Chapin *et al.*, 2010). These dynamics are rendered more complex still by interactions that occur among different scales (Cash *et al.*, 2006), that is across spatial scales (fields, landscapes, regions, etc.) or scales of governance (local, regional, national, etc.).

Third, complex ecosystem sustainability challenges are characterised by the involvement of multiple parties, each with particular interests, values and perspectives, each of which can become an aspect of a complex problem. On the one hand, a wide range of interested parties can provide a wide range of knowledge and resources to collective efforts to address a complex problem. On the other hand, divergence of interests and views among stakeholders impedes mutual understanding (Morriss *et al.*, 2006), may involve irreconcilable differences in worldviews and knowledge systems (e.g. Duncan, 2016), and may give rise to considerable social conflict (Leeuwis, 2000). Because of this range of interests, values and perspectives, any particular ecosystem sustainability challenge is best viewed as comprising a set of diversely defined problems (among which weeds may or may not be salient) that together constitute a multifaceted 'bundle' of problems, rather than any single problem.

Implications of complex problems for efforts to address challenging weed problems

What are the implications of such complexity for weed researchers who wish to address challenging weed problems in the context of broad-based efforts to improve ecosystem sustainability? The most important implication is that the multidimensional, unpredictable and diversely defined nature of complex sustainability challenges must be taken into account in any effort to meet these challenges (Jussaume & Ervin, 2016). For example, if the many causes of complex challenges are not taken into account, problem-solving efforts may overlook important factors. If feedback dynamics are not addressed, processes that insufficiently address long-term impacts may undermine problem-solving. If divergent stakeholder interests and perspectives are not considered, stakeholders may defect from collective action. For these reasons, we argue that researchers that participate in ecosystem sustainability projects must address the inherent complexity of ecosystem sustainability challenges.

Towards transdisciplinary weed research and development (TWR)

What research methods could weed researchers adopt if they wish to participate in ecosystem sustainability projects? We propose that such projects will benefit from an approach, outlined below, that we term 'Transdisciplinary Weed Research' (TWR). TWR is defined as an integrated process of enquiry and action that strives to address challenging weed problems in the context of broad-based efforts to improve economic, environmental and social aspects of ecosystem sustainability. TWR goes beyond current (and laudable) weed research projects that are addressing social factors and pursuing interdisciplinary approaches (e.g. Graham, 2013; Ervin & Jussaume, 2014; Matzek *et al.*, 2014; Zwickle *et al.*, 2014; Seastedt, 2015). These projects are important advances. However, they have tended to be closely framed around weed management, rather than linking to an overarching project of sustainable ecosystem development and a broad complement of stakeholder groups.

To support the continued expansion of weed research towards TWR, we outline a conceptual and practical model for TWR. In articulating this model, we suggest how weed research could engage in transdisciplinary projects on ecosystem sustainability. For example, so-called transdisciplinary synthesis centres for ecosystem science, policy and management (Lynch *et al.*, 2015) are emerging globally. Below, we contribute to the development of TWR by (i) outlining a model for TWR, integrating a range of sources and experiences, (ii) presenting lessons learned from an extensive TWR programme and (iii) exploring opportunities and challenges for weed researchers who want to explore TWR.

Transdisciplinary weed research: key elements

Conceptions of transdisciplinarity range widely (Jahn *et al.*, 2012). We recommend a particular form that was originally articulated by Jantsch (1972). It is highly suitable to addressing challenging weed management problems in the context of work on complex sustainability problems, because it directly addresses the multidimensionality, unpredictability and diversely defined nature of ecosystem sustainability (see also, Hadorn *et al.*, 2008; Lang *et al.*, 2012). First, such transdisciplinarity engages a wide variety of societal stakeholders in collective efforts to characterise diversely defined ecosystem sustainability problems, seeking to clarify their nature and to identify opportunities for collective efforts to address them. Second, the multidimensionality of complex ecosystem sustainability problems is addressed by drawing on a wide range of sources for knowledge relevant to this wide range of dimensions. Finally, this form of transdisciplinary research addresses unpredictability by engaging multiple stakeholders in ongoing, collective efforts to design and implement innovative actions, assess outcomes of these actions and take further action in response to shifts in the situation. Below, we outline the elements of this form of transdisciplinary research.

Determining a course of enquiry and action on complex ecosystem sustainability problems

Jantsch's (1972) conception of transdisciplinary research emphasises the essential role of 'purposive disciplines', which play a crucial role in TWR. Purposive disciplines include ethics, design and other humanistic disciplines. These disciplines identify fundamental moral and ethical issues related to potential courses of enquiry and action, focusing on the critical question of 'what should be done' to address complex problems. Purposive disciplines have emerged as critical to engaging a wide variety of stakeholders in collective efforts on ecosystem sustainability challenges. The purposive disciplines aim to support deliberation and negotiation about such challenges, that is a careful assessment of options, in which stakeholders exchange views about ethical viewpoints and matters of fact, from their points of view. Such interchange creates an opportunity for stakeholders to collectively characterise diversely defined ecosystem sustainability challenges. As well, such interchanges are increasingly valued in innovation processes that can address complex problems (Leeuwis & Aarts, 2011).

For example, the purposive discipline of design has been applied to a project (Opdam *et al.*, 2015) in which a wide range of stakeholders worked to develop non-crop vegetation in an agricultural region of the Netherlands into 'green infrastructure' that would provide a range of desirable ecosystem services to the region, including enhanced pest management. In such roles, the purposive disciplines serve to meet one of the two main challenges of transdisciplinary research on ecosystem sustainability: deliberation and negotiation among divergent stakeholder interests, viewpoints and agendas, in search of some basis for collective action on a scale that can lead to lasting improvements (Opdam *et al.*, 2015).

Needless to say, meeting these challenges of transdisciplinarity is no easy task. Informed by analyses spanning multiple dimensions and levels, deliberation and negotiation about complex problems must address contentious, value-laden issues related to ecosystem sustainability, for example democratic governance of food systems or the distribution of benefits from agricultural research and development (Loos *et al.*, 2014). Given the unpredictable and dynamic nature of complex ecosystem sustainability problems, such deliberation and negotiation are likely to be needed on a recurrent basis. Obviously, engagement of multiple stakeholders around such issues is difficult and may often be unsuccessful due to strong political or values-based conflicts among stakeholders.

However, methods to support effective engagement are emerging from a range of purposive disciplines, such as philosophical dialogue (Eigenbrode *et al.*, 2007), foresight exercises (Quay, 2010), 'public narrative' techniques (Ganz, 2011; Paschen & Ison, 2014) and use of various artistic disciplines to develop provocative scenarios of ecosystem development (Selin, 2014). These approaches use techniques from arts, humanities and design to help participants reframe problems and build mutual understanding across lines of difference. For example, multistakeholder framing efforts improved shared understanding of management of a crop that had potential to escape from cultivation (Friedel *et al.*, 2011). We emphasise that progress in such situations requires adequately resourced efforts to support and advance stakeholder engagement, deliberation and negotiation and to manage attendant conflict. Without such resources and efforts, effective collective action on complex ecosystem sustainability problems is likely to be impossible (Sayer *et al.*, 2013), and therefore, TWR projects are likely to fail.

Integrative analysis of multidimensional and multilevel factors

Successful multistakeholder deliberation and negotiation can lead to agreement on a course of inquiry and action in addressing a complex ecosystem sustainability problem. Such agreement, in turn, can motivate stakeholders to engage in collaborative learning on the problem (Franks, 2010). In Jantsch's conception of transdisciplinary research, collaborative learning, subsequent collective action and critical assessment of the consequences of that action all serve to identify knowledge gaps that are then addressed by relevant applied sciences (e.g. cropping systems research) and more fundamental sciences (e.g. social psychology or soil ecology).

Transdisciplinary research on complex problems relies upon a wide range of knowledge sources, certainly including professional, local, practical and traditional knowledge in addition to scholarly knowledge (Funtowicz & Ravetz, 1994; Staver, 2001). Funtowicz and Ravetz (1994) argued that complex problems must be addressed by expanding the range of knowledge sources deemed valid and relevant including, for example traditional ecological knowledge (Turner *et al*., 2011). This range of sources is necessary because complex problems have biophysical, technological, sociocultural, economic, institutional and political dimensions (Schut *et al*., 2014b). For example, labour limitations in cropping systems related to labour emigration from Guatemalan farming communities enable perennial weeds (e.g. the invasive fern *Pteridium aquilinum* (L.) Kuhn) to emerge as highly intractable problems in tropical agroecosystems (Schneider, 2004). Consequently, exploring and designing sustainable solutions to such problems cannot be successful without analysis of labour supply issues (Spielman *et al*., 2009).

In general, challenging weed problems can be strongly affected by constraints that are outside the direct control of engaging directly in weed management actions. To address these constraints, integrated and multilevel analyses and intervention strategies are needed. These strategies enable holistic analysis of complex and unpredictable ecosystem dynamics, using approaches that consciously draw on a wide range of knowledge sources so as to transcend disciplinary or dimensional modes of knowledge production (Weingart, 2000). Such expansive synthesis is critically needed to guide action on complex ecosystem sustainability challenges, but requires well-facilitated, well-resourced and ongoing efforts, involving multiple cycles of deliberation, research, action and evaluation (Staver, 2001). Recurrent effort is required because complex problems, including their weed-related dimensions, cannot be definitively 'solved', but rather require ongoing management and adaptation. All relevant disciplines and knowledge sources, including the purposive disciplines, are needed as the process goes forward. Successful efforts to build capacity for such efforts are occurring in transdisciplinary synthesis centres for ecosystem science, policy and management (Jahn *et al*., 2012; Lynch *et al*., 2015). Despite its potential value for addressing weed problems, fully developed transdisciplinary research as outlined in this section is largely absent in weed research (Ward *et al*., 2014). To more concretely illustrate how weed researchers might engage in TWR, we now outline a model that describes the conduct of TWR as a recursive process that proceeds through a series of stages.

A process model for transdisciplinary weed research

Our model integrates Jantsch's conception of transdisciplinarity with recent work on transdisciplinary landscape design (Nassauer & Opdam, 2008; Opdam *et al*., 2015; Slotterback *et al*., 2016), adaptive comanagement of landscapes and other spatially extensive ecosystems (Sayer *et al*., 2013), and transformational change in ecosocial systems (Westley *et al*., 2013). The model (Fig. 2) envisions a cyclic process that spans phases of (i) initial problem formulation, (ii) 'broadening' of the problem formulation and recruitment of stakeholder participants, (iii) deliberation, negotiation and design of an action agenda for systemic change, (iv) implementation action, (v) monitoring and assessment of outcomes and (vi) reformulation of the problem situation and renegotiation of further actions. In broad outlines, the model is similar to systems for adaptive comanagement that engage a range of stakeholders in collection action to improve ecosystem sustainability. However, the model accounts for certain challenges that result from the multidimensional, unpredictable

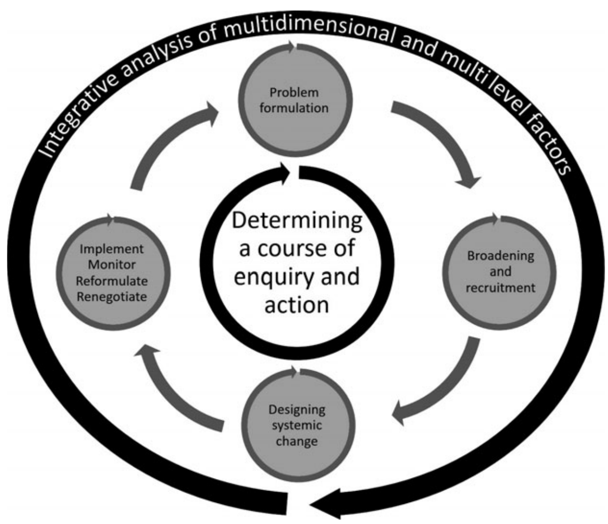

Fig. 2 Process Model for Transdisciplinary Weed Research. Process is initiated by formulation of an ecosystem sustainability problem; the initial problem may concern weeds, or some other aspect of sustainability. Process then proceeds through additional stages, including broadening of problem formulation and recruitment of additional participants, employment of purposive disciplines to design and negotiate a plan for systemic change, and implementation, monitoring of outcomes, reformulation of the problem and renegotiation of further action. Integrative analysis and deliberation regarding the course of enquiry and action are ongoing processes that span the various stages of the process.

and diversely defined nature of ecosystem sustainability problems that are often not recognised in adaptive comanagement models. Purposive disciplines have central, critical and recurrent roles (Opdam *et al*., 2015) in problem formulation, broadening and deliberation/negotiation.

The TWR process begins with initial *problem formulation*, that is the recognition of an ecosystem sustainability problem by a group of stakeholders. This problem may concern weed management, as would be expected if the TWR process is initiated by weed researchers. Alternately, the problem may concern some other aspect of ecosystem sustainability; in this case, weed researchers will join the process in the *broadening* phase, below. The initiating group articulates a statement of the problem and begins collaboration. The group then enters a stage of *broadening and recruitment*, in which it works to recruit other stakeholders into a TWR project by broadening the problem formulation to include aspects that are salient for other stakeholders, creating a 'shared entry point' (Sayer *et al*., 2013) to TWR work on ecosystem sustainability. Often, this phase will be slow and prolonged (Westley *et al*., 2013); complex ecosystem sustainability problems often have no evident solutions when first engaged by a multistakeholder group. During this phase, emphasis is placed on building broad-based understanding of the sustainability problem, using the group's knowledge resources.

Gradually, effort shifts to a phase of *designing systemic change*, using purposive disciplines such as design and scenario planning to collect and integrate knowledge, identify and, if possible, reduce critical knowledge gaps, and to develop options for transformational solutions, while continuing the broadening and recruitment process. Finally, opportunities for *implementation by collective action* of resulting designs are actively sought and taken, after defining roles, rights and responsibilities of participants in implementation (Sayer *et al*., 2013). When action occurs, outcomes are monitored, key knowledge gaps are again identified and closed, and purposive disciplines again come into play in deliberation/negotiation of further action. Examples of similar approaches to transdisciplinary projects on ecosystem sustainability problems are reviewed in Opdam *et al*. (2015) and Sayer *et al*. (2013).

To exemplify operation of this model, we describe its application to challenging weed management issues associated with non-crop vegetation in agricultural landscapes.

Management of such non-crop vegetation is a complex ecosystem sustainability problem. Such vegetation is the source of many ecosystem services, such as habitat for beneficial biodiversity (e.g. pollinators), improvements in water supply and amenity and aesthetic value (Lovell & Sullivan, 2006). However, it is also the source of ecosystem disservices to agriculture, including loss of crop production and habitat for other non-beneficial biodiversity, including weedy and invasive plants. Complex weed management challenges involving such non-crop vegetation include balancing management of undesirable species with conservation of desirable species, avoiding unintended damage from herbicide weed control in field crops (Mortensen *et al*., 2012) and managing stakeholder conflict related to these issues.

We propose that weed researchers can gain new leverage on weed management issues associated with such non-crop vegetation by 'broadening', that is engaging their work on these issues in broader ecosystem sustainability projects. For example, weed researchers could engage in projects pursuing spatial intensification of agricultural landscapes (Heaton *et al*., 2013). Spatial intensification aims to enhance economic, environmental and social sustainability of landscapes by identifying sites in landscapes where locally dominant field crops are poorly adapted and converting such sites to better-adapted crops or non-crop vegetation, thereby increasing crop production and other ecosystem services (Lovell & Sullivan, 2006 Meehan *et al*., 2013; Pywell *et al*., 2015).

Spatial intensification of agricultural landscapes may give weed researchers new leverage on the challenging weed management issues in 'non-crop' areas noted above. Specifically, natural-science weed researchers can help assess and improve approaches to managing the floras of non-field crop elements of these landscapes to support a flora that provides multiple ecosystem services, while limiting ecosystem disservices. Social scientists can investigate a range of social processes relevant to management of such floras. Crucially, the joint enhancement of crop productivity and ecosystem services in spatially intensified landscapes supports 'broadening' by increasing the range of stakeholders that have incentive to join collective action to develop these landscapes. Thus, by participating in spatial intensification projects, weed researchers engage in TWR that creates a wide range of new weed management options, highlights important knowledge gaps and enables weed researchers to target their research to support intensification.

Spatial intensification projects, employing methods that parallel our model for TWR, are not hypothetical. A well-documented example is the case of Hoeksche Waard in the Netherlands (Steingröver *et al*., 2010; Opdam *et al*., 2015) in which a multisector project formed around the goal of reducing pesticide use in a 300 km^2 agricultural district located near several large cities. The plan was to enhance habitat for biocontrol species by expansion and management of lands not used for field crops, which were reconceived in the broadening phase as 'green infrastructure' that provide a wide range of benefits in addition to enhanced biocontrol of crop pests. The project proceeded through stages similar to those outlined in the model above through extensive and recurrent use of a purposive discipline (landscape design, Opdam *et al*., 2015), and heavily engaged pest-management scientists in initial problem formulation and in all subsequent stages. These scientists were motivated to engage in the project because the involvement of other stakeholders enabled the expansion of green infrastructure, in turn creating new possibilities for supporting biocontrol organisms via green infrastructure. The Hoeksche Waard project did not engage weed researchers, but the extensive involvement of other pest-management scientists shows how such engagement can proceed. Below, we further illustrate possibilities for TWR via retrospective and prospective cases.

Retrospective and prospective cases of transdisciplinary weed research

Transdisciplinary weed research in African smallholder agroecosystems

In this retrospective account, we describe collaboration among many scholarly disciplines and societal stakeholder groups that have collaborated in transdisciplinary research on parasitic weeds in the broader context of sustainable development of African smallholder agroecosystems.

Parasitic weeds threaten food and income security in different parts of the world (Parker, 2009). In Africa, the economically most important parasitic weeds in rice production systems are the obligate hemiparasitic witchweeds, *Striga hermonthica* (Del.) Benth. and *S. asiatica* (L.) Kuntze and the facultative hemiparasitic rice vampireweed, *Rhamphicarpa fistulosa* (Hochst.) Benth (Scholes & Press, 2008; Rodenburg *et al*., 2010, 2011). Parasitic weeds in developing countries are a highly challenging problem, deeply embedded in complex sustainability problems of smallholder rice production (Schut *et al*., 2015c).

PARASITE [Preparing African Rice Farmers Against Parasitic Weeds in a Changing Environment (www.parasite-project.org)] was intentionally designed as a TWR programme on parasitic weeds in rainfed rice systems in sub-Saharan Africa and was implemented in Benin, Cote d'Ivoire and Tanzania between 2011 and 2015. The project was initiated based on a growing concern by weed researchers, extension officers and farmers about the increasing emergence of parasitic weeds in rainfed rice systems. PARASITE comprised four interlinked projects that integrated different disciplines (biology/ecology, agronomy, economy and sociology), which operated at different integration levels (plant, field, farm, region and nation) and involved a variety of societal stakeholders (farmers, private sector, policymakers and development partners) throughout the different phases of the programme (problem formulation and analysis, priority setting and implementation and evaluation of interventions).

Broadening activities sought the active involvement of a wide range of social sectors, which provided professional, local, practical and traditional knowledge, and deliberated the merits of potential actions. This engagement was facilitated through a series of multistakeholder workshops in which constraints and opportunities for innovation to address parasitic weeds were identified (Schut *et al*., 2015a). The majority of stakeholder constraints related to broader challenges in the crop protection and agricultural system than to parasitic weeds specifically (e.g. performance of agricultural extension services and poor collaboration between stakeholders (Schut *et al*., 2015b)). According to stakeholders, efforts to address these constraints were promising strategies, with potential to improve parasitic weed management while also addressing other sustainability problems in these production systems.

These engagement activities facilitated data analysis and interpretation by scientists from a range of disciplines (including weed scientists) in collaboration with different societal actors. The result was a multidimensional and multilevel view of problems related to parasitic weeds in rainfed rice systems. This view then enabled design of integrative solutions. For example, the approach created a systemic understanding of multiple factors that affected a potentially effective parasitic weed control strategy, namely use of organic and inorganic fertilisers on improved rice varieties by farmers (Rodenburg *et al*., 2011). It demonstrated that the use of fertilisers was strongly affected by the following factors:

- Technological: some farmers were afraid of undesired side effects of fertilisers on the crop, for example increased weed abundance;
- Sociocultural: farmers were concerned that use of improved crop varieties would contaminate aromatic qualities of local rice varieties;
- Economic: purchasing power of farmers was low;
- Institutional: lack of quality control of agricultural inputs lead to adulteration of crop protection chemicals, fertiliser and seeds, which discouraged farmers from investing in such products (Rodenburg *et al*., 2015).

In the PARASITE programme, the transdisciplinary approach ensured that parasitic weed management strategies were (1) developed and evaluated through researcher–farmer collaborations (agronomy), (2) based on biological and ecological insights (biology/ecology), (3) locally available and affordable (economy) and (4) acceptable for different stakeholder groups across different levels (sociology). This increased the likelihood that robust, applicable and widely supported solutions could be developed and implemented. For example, participatory research projects on novel systemic approaches to parasitic weed management have emerged from PARASITE. These projects, which were not envisioned at the outset, arose from observations that parasitic weeds are associated with poor soils and that affected farmers are among the poorest and cannot afford expensive fertilisers. These observations inspired discussions regarding alternative management strategies that could increase soil fertility for such farmers. Based on such discussions between researchers, extension officers and farmers, farmer participatory trials using rice husks or animal manure as soil fertility amendments were established (Rodenburg *et al.*, 2015). Farmer surveys in Tanzania demonstrated that awareness of parasitic weeds is much higher in study sites where the participatory trials were implemented, as compared with study sites where no participatory trials were established (Schut *et al.*, 2015c).

Reflective evaluation of the PARASITE programme emphasised the importance of an institutional environment for TWR that can support the significant costs associated with efforts to understand and integrate concepts, methods, needs and interests (Rodenburg *et al.*, 2015). In PARASITE, researchers represented both fundamental and applied international agricultural research institutes, which enhanced engagement of the programme and its results, while also increasing costs related to travelling, telecommunication and interaction and collaboration between those involved. Moreover, aligning research strategies with the needs and interests of societal stakeholders and changing research contexts requires ongoing adaptation. Yet, funding requirements and incentive structures often require research to be undertaken as prescribed 'projects' rather than 'processes' of inquiry, inhibiting development of unanticipated unifying visions and other emergent outcomes. Rather, activities and outcomes are typically planned and proscribed in advance of research, leaving little room for unexpected outcomes. Restructuring research programmes to account for these emergent dynamics will enable weed researchers to explore the potential of TWR. Options for restructuring include flexible budgets, planning and monitoring, participatory R&D planning and budgeting, and active facilitation of multistakeholder processes (Schut *et al.*, 2015d). Additionally, scientists need to be incentivised to actively engage with societal stakeholders to identify relevant research and development questions and develop joint outputs with colleagues from different disciplines (Schut *et al.*, 2014b).

A prospective case of transdisciplinary weed research

We now describe plans for TWR in a newly formed project, drawing upon insights into the retrospective case concerning flexibility in budgeting, planning and monitoring, with an eye to proactive 'broadening' and emergent outcomes. A newly formed (2015) USDA-Agricultural Research Service Area-Wide project is addressing multiple herbicide-resistant (MHR) weeds across three distinct grain-producing regions of the USA (north central, south central and mid-Atlantic). These weeds are challenging sustainable crop production, particularly in reduced- and no-tillage production systems, which have important soil-conservation benefits. Such weeds have become widespread, rapidly rendering herbicide weed control less effective, while the pace of herbicide discovery has greatly slowed. The project is titled *An Integrated Weed Management Approach to Addressing the Multiple Herbicide-resistant Weed Epidemic in Three Major U.S. Field Crop Production Regions* and currently involves 25 researchers from 18 research institutions (including co-authors Davis, Ervin, Mirsky and Jordan). The project aims to identify, evaluate and promote integrated weed management systems that can help producers regain control of MHR weeds in highly affected U.S. grain production regions, while avoiding reversion to intensive mechanical weed control, which will threaten decades of progress in soil conservation via reduced tillage.

At present, the project is working to expand towards transdisciplinarity. Many members are primarily focused on natural-science weed research, but the project has been designed from the beginning as an interdisciplinary project, enrolling several social scientists in addition to natural scientists addressing plant physiology, molecular biology, agronomy and soil science. Economists are participating to analyse the economic cost and benefit of numerous integrated weed management tactics, determine the socio-economic challenges and opportunities to adoption of such tactics and provide economic perspectives on spatially co-ordinated management strategies (farm vs. community-based approach). Preliminary project findings show (Evans *et al.* unpublished) that co-ordination of weed management decisions among farmers at landscape scales can substantially hinder the evolution and spread of herbicide resistance. Currently, the project is actively undertaking 'broadening' of the MHR problems, seeking to couple the project with other work that share similar goals for agroecosystem sustainability. These activities are central to the broadening phase of the process model we propose for TWR (Fig. 2).

This phase is guided by an important premise of the project: diversification of weed management and crop rotation is necessary to enable durable management of herbicide resistance in weeds. Therefore, the project is establishing contacts with other groups and organisations concerned with economic, environmental and social diversification of maize/soya bean production systems and the agricultural landscapes in which these systems function. These groups include efforts focused on soil health, climate resilience, stewardship of water resources and conservation of biodiversity (e.g. pollinators). All of these groups share a fundamental interest in diversification of cropping systems and agricultural landscapes. Another avenue of broadening is engagement with firms involved in agricultural equipment (e.g. harvesting machinery) and agrichemical production and application.

A particular emphasis of broadening work is exploring shared interests in spatially co-ordinated management of diversified agricultural landscapes. Much evidence shows the value of such approaches for soil, water and biodiversity conservation (Sayer *et al.*, 2013), but a range of conditions is needed for implementation (Ervin & Frisvold, 2016). Therefore, a collective research and education effort to meet such conditions is a highly promising opportunity for broadening towards transdisciplinarity. In particular, the project is considering collaborative experiments with co-ordinated management that can help manage MHR weeds and enhance water, soil and biodiversity. These projects can draw on successful applications of the purposive discipline of landscape design to motivate multistakeholder participation in such approaches (Opdam *et al.*, 2015; Slotterback *et al.* 2016), as well as emerging social innovations for co-ordinated management, such as farmer-led 'working lands conservation partnerships' (Duncanson *et al.*, 2014) and watershed protection utilities (US Water Alliance, 2014).

Exploring opportunities and constraints for transdisciplinary weed research

TWR may have considerable potential to enable new progress on challenging weed problems and to extend or complement current weed research. To explore this potential, weed researchers can build on the successes of current interdisciplinary weed research initiatives that link natural and social science (e.g. Riemens *et al.*, 2010; Friedel *et al.*, 2011; Ervin & Jussaume, 2014). As noted above, these laudable projects generally do not yet support the full range of processes outlined in the TWR model that we have described (Fig. 2).

We observe that society is providing increasing incentives for researchers to make use of the processes inherent in the TWR model. For example, systemic and transdisciplinary approaches are increasingly required by public funding agencies that are relevant to weed research; the main US federal funding agency for agricultural research has explicitly called for 'systems-based, trans-disciplinary projects' in a range of relevant recent funding opportunities (USDA NIFA, 2015; http://nifa.usda.gov/resource/planning-and-managing-systems-based-trans-disciplinary-projects-usdanifa-programs). Generally, funding agencies and universities are increasingly focusing on complex 'grand challenge' problems (e.g. climate change adaptation)[1]; we believe that by exploring and refining TWR, weed researchers can highlight the relevance of weed research to such 'grand challenge' problems.

To support continued exploration of TWR, we recommend formation of an informal 'community of practice' (Wenger, 2000), comprised of weed researchers, to address the relationship between weed research and transdisciplinarity. Communities of practice are groups of persons who share some goal and interact on an ongoing basis to accelerate mutual progress towards that goal via learning (Wenger, 2000). Given the strong interest in expanding the scope of weed and pest-management research (Davis *et al.*, 2009; Allen *et al.*, 2014; Schut *et al.*, 2014a; Ward *et al.*, 2014), we expect that a community of practice could readily be formed under the auspices of one of the weed research professional organisations, similar to the interest-based 'communities' that are supported by the American Society of Agronomy (ASA, 2016). We envision that TWR could proceed by convening participants in a range of TWR projects. The community would support a reflective process (Schön, 1983), in which weed researchers critique and refine approaches for TWR and consider how best

[1]UNSW currently has a list of 'grand challenges' that it is seeking to address, climate change being one of them (http://grandchallenges.unsw.edu.au/). The University of Melbourne also has 'grand challenges' including 'supporting sustainability and resilience' (http://research-vision.unimelb.edu.au/content/grand-challenges).

to respond to barriers and incentives relevant to TWR. The goal would be to advance research on challenging weed problems by strong feedback between conceptual development and the actual practice of TWR. Communities of practice require resources for their organisation and for active facilitation of activities.

To carry out this programme of exploration, crucial limiting factors must be overcome. As is commonly observed, and highlighted in the PARASITE case, current institutional and incentive structures often discourage, rather than encourage, transdisciplinary research (Lang *et al.*, 2012; Schut *et al.*, 2014a; Campbell *et al.*, 2015). A major challenge arises from the opportunity and transaction costs of organising transdisciplinarity. As is well documented (e.g. by Stokols, 2006), relatively long periods are often needed to integrate work in scientific disciplines with other academic disciplines, and, more broadly, to engage in social processes relevant to transdisciplinary research. Such processes include integration of knowledge from a wide range of scholarly and practice-based sources (Bammer, 2012; Rodenburg *et al.*, 2015), and the building of trusting relationships for multistakeholder collaboration in innovation activities (Leeuwis & Aarts, 2011), collective action and participatory democratic governance (Gaventa, 2006). At present, these processes cannot be expected to self-organise. It would seem that their organisation and leadership is the collective responsibility of transdisciplinary researchers, including but not limited to weed researchers (Schut *et al.*, 2014a; Campbell *et al.*, 2015). Given current impediments to transdisciplinarity, we suggest that sustained collective action by a community of practice is the most likely way forward. We believe that universities, research organisations and professional societies are best positioned to initiate or catalyse such efforts; these institutions have strong incentives to advance their research methods to ensure outcomes that will be recognised and supported by society.

We also call for consideration of transdisciplinary research in graduate education. In most cases, graduate training in sciences relevant to weed research largely focus on a few scientific disciplines, with little curriculum devoted to complex problems. In response, Wiek *et al.* (2011) called for development of capacities including strategic and systemic thinking, competence in purposive deliberation (i.e. discourse in which ethics, values and norms are in question), capacity in effective and purposeful engagement of stakeholders, and development of relevant interpersonal skills.

Conclusions

We argue for systemic approaches to challenging complex weed problems (e.g. herbicide resistance or extensive plant invasions in natural areas). These approaches can create new opportunities to manage root causes of such problems and improve complementarity between weed management and other activities. However, systemic approaches are difficult and costly, because of the inherent complexity of the ecosystem sustainability problems that underlie most challenging weed problems. TWR, as outlined and exemplified above, is designed to engage such complexity. TWR requires the integration of a range of scholarly disciplines and the active and ongoing engagement of societal stakeholders. A conducive institutional environment is essential, as are resources to facilitate collaboration between and joint action by scientists and societal stakeholders. Flexibility and adaptive management is required to respond to changing stakeholder priorities and context. To advance conceptual and practical development in TWR, we call for a community of practice that experiments with TWR and reflects critically on methodology and outcomes.

We conclude with several suggestions for weed researchers who may wish to apply the TWR model we have outlined to address challenging weed problems. First, it is vital to recognise that the TWR model requires extensive organising and facilitation before outcomes can be attained. Such efforts are critical to managing the inherent complexity of sustainability in managed ecosystems. Therefore, TWR requires patience, investments in broadening and recruitment so as to form relationships with like-minded collaborators, ongoing critical reflection on project progress and a willingness to engage with social aspects of sustainability, including issues such as democratic governance of managed ecosystems. Patience and persistence are likely to be tested by competing interests and conflict that is often present in multistakeholder processes (Giller *et al.*, 2008). Furthermore, efforts to 'do things differently' may challenge established institutions and understandings of the nature of weed research, which may generate misunderstandings, tension and resistance (Schut *et al.*, 2016). In some situations, integration of knowledge and agendas across stakeholders and sectors may be difficult or impossible (Duncan, 2016).

Weed researchers are not, in our view, solely responsible for developing projects in which TWR can be practiced, but should be willing to take some part in initiation and organisation of such projects. At a minimum, we recommend that weed researchers interested in challenging weed problems should gain some awareness of TWR methods, so as to be able to recognise opportunities to engage their work in broad-based ecosystem sustainability projects. Finally, if inclined by interest and personality, weed researchers could consider playing active organising roles in such projects. We emphasise that TWR cannot replace disciplinary weed research; rather, it is a strategy for leveraging and complementing such research, in situations where inherent complexity may limit its impact.

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